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THE MORPHOLOGY OF

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D. G. Dartt, R. W. Wilcox and A. D. Belmont

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The purpose of this paper is to compare sudden warmings to find any consistent behavior of the important variables. The properties examined are amplitude and phase of planetary waves, sensible heat and momentum fluxes by each wave, and zonal means of geostrophic zonal wind, temperature, derived meridional wind and vertical motions. This is done for the seven warmings from 1970-74 for which daily gridded data up to 0.4 mb were available. Cont....

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20. Wave number 1 in the stratosphere is the major disturbance for each warming. The sequence of poleward heat flux by this wave is the most systematic process observed, so other variables are described at four characteristic stages of this heat flux cycle: pre-warming (equatorward heat flux at 2 mb), intermediate warming (maximum poleward heat flux at 200 mb), maximum warming (maximum poleward heat flux at 2 mb) and post-warming (equatorward heat flux at 2 mb). When analyzed in this manner, all variables behave quite similarly during all warming events.

During intermediate and maximum warming steps, an indirect thermal meridional cell occurs, as described by Matsuno (1971), with poleward transport of heat by wave 1, ascending motion over the pole, northerly flow at high altitudes in polar regions and descending motion in middle latitudes. There is some evidence for a direct meridional cell with the signs of all parameters reversed during the initial pre-warming state.

Some precursors of sudden stratospheric warmings appear to include the occurrence of a strong westerly jet or strong easterly shear in the upper stratosphere some two to five weeks before the maximum stratospheric heat flux, and the occurrence of equatorward heat fluxes in the stratosphere at about this same time. Also, the 200-mb heat flux maximum occurs two to seven days before the stratospheric maximum. These characteristics would appear to be useful for predicting the occurrence of sudden warmings and the intensity of the resulting zonal heating.

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SUMMARY OF REPORTS PREPARED ON THIS CONTRACT

Two primary studies have been completed during this investigation.

A. Planetary Waves of Height and Temperature Fields.

Geopotential height grids were prepared from data sets previously derived from SCR-B data and planetary waves of temperature on a global basis and geopotential height for the Northern Hemisphere were calculated. The above planetary wave computation was repeated for an earlier segment of temperature and geopotential height grids based on SCR-A radiance data. The result of both computations were daily time series of planetary wave coefficients of height and temperature for the period April 1970 through December 1974. A global analysis of the behavior of the major temperature waves was prepared. Results showed: (1) the presence of seasonal planetary wave regimes in the upper stratosphere when the zonal phase velocities of the waves remains either eastward, westward, quasi-stationary or random for extended duration. Further, phase velocities of traveling waves 1 and 2 in the upper stratosphere are functions of zonal wind velocity and undergo a seasonal variation. (2) A well-defined small amplitude westward traveling wave 2 component in the upper stratosphere was found that had been previously detected only at lower levels. This wave exists primarily during the spring and summer months and has a period of about four days. (3) Time periods were found when waves 1 and 2 exist coherently across the equator in both hemispheres. Details were described in an Interim Scientific Report, "The Morphology of Stratospheric Planetary Waves, 10 to 0.4 mb" by D. G. Dartt, R. W. Wilcox, and A. D. Belmont, July 25, 1980. In addition, a paper entitled, "Morphology of Planetary Wave Number 2 in Temperature, 10 to 0.4 mb" was delivered at the 1981 American Meteorological

Society Upper Atmosphere meeting in San Diego. Currently, some of the major results of these efforts are being summarized for submission to a scientific journal. A copy of the Interim Report is enclosed for convenient reference.

B. Diagnosis of Sudden Warmings.

The second study analyzed seven stratospheric sudden warmings that occurred during the interval 1970 to 1974. This involved additional computation of planetary waves of height and temperature downward into the troposphere to 850 mb, the calculation of planetary waves in zonal and meridional wind, the computation of sensible heat and momentum fluxes by the planetary waves, and calculation of zonally averaged vertical motion and meridional wind. All these variables were compared for seven sudden warming events. All seven sudden warmings exhibited similar behavior in terms of wave 1 heat flux, wave 1 momentum flux, and zonal means of temperature, vertical motion and meridional wind. A suggestion is made that monitoring the heat flux by the major waves and zonally averaged winds from the surface to high stratospheric levels on a daily basis during the winter months would allow the prediction of zonal heating during sudden warmings sometime in advance.

This analysis is described in the following report: "Diagnosis of Seven Stratospheric Sudden Warmings Using Wave Parameters from 850 to 0.4 mb, 1970-1974", by D. G. Dartt, July 5, 1981. This paper is currently being submitted for publication.

DIAGNOSIS OF SEVEN STRATOSPHERIC SUDDEN WARMINGS USING WAVE PARAMETERS FROM 850 TO 0.4 MB, 1970-1974

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July 1981

(To be submitted for publication)

ABSTRACT

The purpose of this paper is to compare sudden warmings to find any consistent behavior of the important variables. The properties examined are amplitude and phase of planetary waves, sensible heat and momentum fluxes by each wave, and zonal means of geostrophic zonal wind, temperature, derived meridional wind and vertical motions. This is done for the seven warmings from 1970-74 for which daily gridded data up to 0.4 mb were available.

Wave number 1 in the stratosphere is the major disturbance for each warming. The sequence of poleward heat flux by this wave is the most systematic process observed, so other variables are described at four characteristic stages of this heat flux cycle: pre-warming (equatorward heat flux at 2 mb), intermediate warming (maximum poleward heat flux at 200 mb), maximum warming (maximum poleward heat flux at 2 mb) and post-warming (equatorward heat flux at 2 mb). When analyzed in this manner, all variables behave quite similarly during all warming events.

During intermediate and maximum warming steps, an indirect thermal meridional cell occurs, as described by Matsuno (1971), with poleward transport of heat by wave 1, ascending motion over the pole, northerly flow at high altitudes in polar regions and descending motion in middle latitudes. There is some evidence for a direct meridional cell with the signs of all parameters reversed during the initial pre-warming state.

Some precursors of sudden stratospheric warmings appear to include the occurrence of a strong westerly jet or strong easterly shear in the upper stratosphere some two to five weeks before the maximum stratospheric heat flux, and the occurrence of equatorward heat fluxes in the stratosphere

at about this same time. Also, the 200-mb heat flux maximum occurs two to seven days before the stratospheric maximum. These characteristics would appear to be useful for predicting the occurrence of sudden warmings and the intensity of the resulting zonal heating.

1. Introduction

Holton (1975) and Schoeberl (1978) have reviewed the most important observational and theoretical features of sudden warmings; the reader is referred to these articles for an historical perspective. With the advent of satellites measuring thermal radiance in the stratosphere, new observational studies of warmings were initiated, allowing the first hemispheric analysis at altitudes where the temperature increases are most intense. The SCR instruments on Nimbus 4 and 5 took measurements of the thermal structure of the stratosphere upwards to 0.4 mb on a daily basis during the interval April 1970 to December 1974. This data has been used to conduct synoptic history studies of the major mid-winter warmings of 1970-71 (Barnett et al, 1971; Labitzke, 1972; Petzoldt, 1973; Klinker, 1977) and of 1972-1973 (Crane, 1979; Kanzawa, 1980). Quiroz (1975) and Quiroz et al. (1975) have also synoptically described warming events for basically this same period using the SIRS and VTPR radiance measurements from NOAA satellites.

The analysis here describes seven sudden warmings that occurred during the 1970-74 interval using planetary scale wave parameters from 850 to 0.4 mb. Two of these warmings were major mid-winter events described above; also included are three minor mid-winter warmings and two final spring warmings that occurred during this time interval (Table 1). The purpose of this paper is to compare sudden warmings to find any consistent behavior of the important variables. The properties examined are amplitude and phase of planetary waves, sensible heat and momentum fluxes by each wave, and zonal means of geostrophic zonal wind, temperature, derived meridional wind and vertical motions.

Warming	Time	Type	Δ [T](^{o}K)	Δ [u](m sec^{-1})
A	12/5/70-1/20/71	Major-midwinter	46 (75 N)	-92 (65 N)R
B	2/9/71 -4/9/71	Final-spring	42 (75 N)	-61 (65 N)R
C	12/21/71-1/9/72	Minor-midwinter	21 (65 N)	-91 (55 N)
D	12/16/72-1/15/72	Minor-midwinter	28 (75 N)	-42 (55 N)
E	1/15/72-1/28/72	Major-midwinter	20 (75 N)	-53 (65 N)R
F	12/14/73-1/13/74	Minor-midwinter	21 (55 N)	-21 (45 N)
G	2/1/74 - 3/1/74	Final-spring	42 (75 N)	-70 (55 N)R

Table 1 - Zonal temperature increase, Δ [T], and west wind deceleration, Δ [u], for warming events at 2 mb. R indicates that a zonal wind reversal from west to east occurred at 2 mb.

Matsuno (1971) was one of the first to successfully describe many observed features of sudden warmings using a numerical model based on the interaction of planetary scale waves and the zonal flow. He suggested that large amplitude vertically propagating planetary waves from the troposhere are the source of the warming. In the stratosphere these waves transport sensible heat poleward, and in the region of heat flux convergence near the pole cause the zonal mean temperature to increase and ascending motion to occur. In contrast, in the region of heat flux divergence in lower latitudes zonal cooling and descending motion will occur. A zonally averaged northerly wind component at stratospheric altitudes completes the meridional cell. This north wind can decelerate the westerly winds of the polar vortex through the action of the Coriolis torque and maintain a thermal zonal wind balance with the meridional temperature field. With the deceleration of west winds at high altitudes, a critical level may eventually be formed which restricts the upward propagation of planetary waves. Immediately beneath this critical level, further warming occurs as a result of heat flux convergence. This results in further deceleration of the zonal flow and lowering of the critical level to a lower altitude. This process appears to describe the descending zonal temperature maximum and wind minimum (easterlies) that are characteristic of most warmings. Most recently, the additional consideration of momentum fluxes by the waves helps to better model the observed wind pattern (Holton, 1976; O'Neill, 1980).

Tung and Lindzen (1979a, 1979b) considered the cause of planetary wave amplification that is required to initially begin the warming process. In their theory of resonant Rossby waves "wave amplification occurs when the flow in the atmosphere is such that free-traveling Rossby waves of a certain zonal wavenumber and meridional structure are rendered stationary

with respect to the surface of the earth, and hence can resonantly interact with the forcings of topography and differential heating which are stationary". Tung and Lindzen (1979b) indicate that before resonance can occur, the vertically propagating wave must be trapped below the middle stratosphere. An easterly shear region above a descending stratospheric westerly jet appears most favorable for trapping waves 1 and 2. Once trapping occurs, a variety of observed wind profiles between the ground and the turning point appear to satisfy the condition for resonance. One of the free Rossby modes that may be involved in the warming process is the 15-day westward propagating mode (Madden and Labitzke, 1981). This wave commonly appears in the winter stratosphere and interacts with the stationary wave to cause perturbations in the poleward heat transport.

2. Data

Practically all parameters were computed from daily planetary wave coefficients of height and temperature for wave numbers 0-6. This calculation was performed for seven latitude circles (25, 35, 45, 55, 65, 75, 79N) and 11 altitudes (850, 500, 200, 100, 50, 30, 10, 5, 2, 1, and 0.4 mb) for the winter season (October 15 to April 15) from 1970-1974. For the six lowest levels, wave amplitude and phase are based on NMC gridded values interpolated to 20° longitude intervals. The zonally averaged west wind analysis below 100 mb is derived from NMC wind grids; otherwise all wave analysis for wind is based on the geopotential height field using the geostrophic approximation as described by Eliasen (1958). Waves at the five upper levels are based on temperature fields derived statistically from NMC 10-mb temperature and various nonlinear combinations of SCR channel

radiances from Nimbus 4 and 5. The regression coefficients utilized in the temperature analysis were derived from co-located rocketsonde temperature, NMC 10-mb temperature and smoothed satellite radiances. Hovland and Wilcox (1979a, 1979b) give a detailed discussion of the regression and gridding procedures. The upper level geopotential height fields were derived hydrostatically using the NMC 10-mb height field and the statistically derived upper-level temperature fields.

3. Wave Parameters

a. Wave 1 Heat Flux

The prominent mechanism for increasing the temperature in polar regions during warmings is poleward transport of sensible heat by large-scale waves. The product of the amplitude of the zonal wave in temperature and the amplitude of the zonal wave in meridional wind and the cosine of the phase difference of these waves determines the poleward heat flux (vT) for that wave. This parameter was computed daily for each wave (k=1,6) from 850 to 0.4 mb. The meridional wind wave was determined geostrophically from the geopotential height wave. When the temperature wave is displaced to the west of the height wave, poleward heat transport occurs with the maximum heat flux corresponding to a phase difference of one quarter wavelength. With a westward displacement of the temperature wave, the height wave slopes westward with altitude as a result of hydrostatic adjustment. Thus, a westward shift in phase with altitude indicates poleward heat transport and also upward propagation of wave energy provided the zonal wind is westerly relative to the phase velocity of the geopotential height wave (Eliassen and Palm, 1960).

Of the seven Northern Hemisphere warmings observed during the April '70 - December '74 interval, temperature wave 1 predominates over wave 2 at stratospheric levels (Table 2). At 200 mb wave 1 and wave 2 are of comparable magnitude. A similar relation is evident for wave 1 and 2 heat fluxes.

Figure 1 indicates the wave 1 transport of heat at 65N for all seven warmings. For each event, there is strong poleward heat transport in a layer from 200 to 2 mb with a maximum value at the upper level. Above 2 mb, the poleward heat flux diminishes and for some warming events (A and B) changes direction to equatorward. The 2-mb heat flux appears larger during major than minor warmings (Tables 1 and 2). Figure 1 further indicates that an early maximum value of poleward heat flux occurs in the upper troposphere usually more than one week before the 2-mb maximum value. By the time the 2-mb maximum value occurs, the tropospheric heat flux often has changed direction towards the equator (events A, B, C, F).

For each warming a common sequence is:

(1) Pre-warming - an initial state when equatorward heat flux occurs just prior to a switch to poleward heat transport over a significant portion of the atmospheric column;

(2) Intermediate warming - 10 to 25 days later when poleward heat flux reaches a maximum at 200 mb;

(3) Maximum warming - 2 to 20 days later still when poleward heat flux becomes maximum at 2 mb;

(4) Post-warming - 2 to 30 days still later when the heat flux at 2 mb again becomes directed towards the equator.

These four characteristic steps (times) are indicated by dates on each time section (Figure 1). (Note, warmings D & E are two major heat

Warming	Pressure(mb)	$\Delta[T]$(°K)	T_1 (°K)	T_2 (°K)	v_1T_1 (°K m s^{-1})	v_2T_2 (°K m s^{-1})
A	2	46 (75 N)	37 (65 N)	11 (55 N)	855 (75 N)	79 (55 N)
	30	30 (75 N)	22 (65 N)	8 (65 N)	159 (75 N)	49 (65 N)
	200		10 (65 N)	7 (45 N)	37 (65 N)	38 (45 N)
B	2	42 (75 N)	23 (65 N)		348 (75 N)	
	30	14 (75 N)	13 (65 N)	8 (65 N)	102 (75 N)	24 (65 N)
	200		13 (65 N)	13 (65 N)	34 (75 N)	26 (65 N)
C	2	21 (65 N)	17 (65 N)	12 (45 N)	196 (65 N)	120 (55 N)
	30	9 (65 N)	18 (65 N)	11 (55 N)	74 (65 N)	41 (55 N)
	200		8 (65 N)	6 (45 N)	26 (65 N)	39 (45 N)
D	2	25 (65 N)	20 (55 N)	13 (55 N)	393 (75 N)	54 (65 N)
	30	8 (75 N)	18 (65 N)	8 (55 N)	95 (75 N)	30 (55 N)
	200		8 (55 N)	7 (55 N)	22 (75 N)	51 (55 N)
E	2	10 (75 N)	32 (65 N)	12 (55 N)	600 (75 N)	72 (65 N)
	30	22 (75 N)	19 (65 N)	7 (55 N)	135 (65 N)	28 (65 N)
	200		14 (75 N)	7 (55 N)	69 (75 N)	20 (55 N)
F	2	21 (55 N)	23 (45 N)	12 (55 N)	247 (75 N)	80 (55 N)
	30	12 (75 N)	22 (65 N)	10 (55 N)	128 (75 N)	32 (55 N)
	200		13 (55 N)	7 (55 N)	37 (55 N)	62 (65 N)
G	2	42 (75 N)	33 (75 N)	22 (65 N)	660 (75 N)	74 (55 N)
	30	20 (75 N)	23 (55 N)	7 (55 N)	138 (65 N)	48 (65 N)
	200		13 (55 N)	8 (65 N)	51 (75 N)	35 (65 N)

Table 2. Maximum values of zonal temperature change ($\Delta[T]$), amplitude of temperature wave 1 (T_1) and wave 2 (T_2), and heat transport by wave 1 (v_1T_1) and wave 2 (v_2T_2) for warming events. The latitudes of the maxima are indicated in parenthesis.

flux perturbations with January 15, 1973 being the date corresponding to post-warming for the first perturbation and pre-warming for the second perturbation.) In the remaining analysis, these characteristic steps are used to examine other wave parameters relative to this observed cycle of heat transport.

b. Wave 1 Phase and Amplitude for Geopotential Height.

In Figure 2 the phase profile is given on days corresponding to the characteristic warming steps of the heat flux cycle for each warming event. Note that the phase profile for the intermediate and maximum warming dates slopes almost uniformly westward from 500 mb to 0.4 mb, a condition for optimum vertical transport of wave energy. In contrast, for pre-warming and post-warming dates, segments of the phase profiles exhibit eastward slopes with altitude.

During the four winters studied, the occurrence of sudden warmings appears related to periods of time of at least one-week duration when the westward shift in phase with altitude of wave 1 is apparent from near the earth's surface to well into the upper stratosphere. Often during these winters poleward heat transport occurred in the stratosphere; however, in the troposphere the westward shift in phase with altitude of wave 1 was not apparent. Under these conditions sudden warmings did not occur.

A rather narrow range of phase at each level from 500 mb upwards to 5 mb is evident when all warming events are considered during times of intermediate and maximum warming (Figure 2). This is also shown in Table 3 and suggests that warmings may be associated with amplification of a tropospheric controlled stationary wave near the earth's surface, as described by Tung and Lindzen (1979a). Warmings have frequently been associated with

Event	Intermediate Warming				Maximum Warming			
	ϕ_z(500mb)	ϕ_T(500mb)	ϕ_z(200mb)	ϕ_T(200mb)	ϕ_z(5mb)	ϕ_T(5mb)	ϕ_z(2mb)	ϕ_T(2mb)
A	29W	31W	37W	144W	178W	110E	149E	101E
B	47E	46W	13W	117W	168W	119E	152E	107E
C	5E	10W	9W	133W	155W	84E	157W	32E
D	33E	35E	13E	69W	170E	113E	148E	47E
E	29W	14W	49W	101W	166W	109E	145E	75E
F	3W	5W	45W	90W	164W	155E	176W	96E
G	37E	25W	21W	102W	157W	136E	179W	83E

Table 3. Phase angle of height , ϕ_z, and temperature ϕ_T, (longitude of wave 1 maximum) at 65^{O}N for intermediate and maximum warming steps of heat flux cycle.

the intensification of the Aleutian anticyclone in the upper stratosphere. The longitude of geopotential wave 1 maximum at 5 mb indicates that this synoptic feature was prominent in all warming events studied here. Table 3 also indicates that at the time of intermediate warming, the temperature and height waves at 500 mb are almost in phase (barotropic) except for events B and G. However, between 500 and 200 mb, the temperature wave is displaced westward almost 90^{0}, creating the opportunity for large poleward heat flux. This displacement to the west of the temperature wave relative to the geopotential wave is maintained later in the upper stratosphere during the time of maximum warming.

Figure 3 indicates there is generally a good correspondence between the amplitude of wave 1 height and the magnitude of wave 1 heat transport upwards to 2 mb (Figure 1) during the pre-warming, intermediate and maximum warming stages of the heat flux cycle. In the post-warming stage, the correlation is poorer when on occasion a large amplitude peak in height is associated with negative (equatorward) heat transport near 2 mb (events C and G).

In the upper stratosphere, from 1 to 0.4 mb, the growth of wave 1 amplitude during warmings is often restricted (Figure 3). At these times, temperature and geopotential height are frequently almost 180^{0} out of phase, and hydrostatically, any increase in temperature amplitude leads to a decrease in amplitude of geopotential height. Figure 4 is an example of phase difference between temperature and height waves for warming A and can be compared to Figure 3A. Note, height and temperature are frequently out of phase in the stratosphere and also in the troposphere during pre-warming and post-warming steps leading to a decrease in wave 1 amplitude at neighboring higher levels.

c. Zonal Temperature Change

Heat flux convergence contributes to the increase in mean zonal temperature in the polar stratosphere. Conversely, net cooling is often observed in the subtropics, corresponding to the region of heat flux divergence (Fritz and Soules, 1972). Cross sections depicting the initial pre-warming temperature state and subsequent changes at various stages of the heat flux cycle for each warming event are presented in Figure 5. Warming in middle and high latitudes from 5 to 2 mb occurs between pre-warming and intermediate warming steps except for events D and E where zonal heating is delayed. From the time of intermediate warming to maximum warming the zonal heating intensifies near the pole and moves downward to 5 and 10 mb. Weak cooling at 25N in the sub-tropics, 2 to 10 mb, is observed at this time for each warming event. In the time interval from maximum warming to post-warming, zonal heating continues to move downward in polar regions with levels from 30 to 200 mb often being heated at 65 and 75N During the descent of the zonal heating, cooling is evident at still higher altitudes in polar regions for events A, D, E and G.

d. Zonal Wind Change

The increase in zonal temperature in the polar stratosphere because of the warming process weakens the winter pole-to-equator temperature gradient resulting in a deceleration of westerly winds in middle and polar latitudes. Figure 6 depicts this deceleration process for the various warming events as a function of the previously defined steps of the heat flux cycle. Cross-sections of the wind field at the initial pre-warming state indicate on most occasions strong west winds of at least 100 m s^{-1} at 45N, 0.4 mb, associated with the polar night jet. The strengthening

of the polar night jet will increase the easterly vertical shear immediately above the jet which may help originate the warming process by trapping upward propagating large-scale waves resulting in wave amplification at lower levels (Tung and Lindzen, 1979b). On each occasion during the four-year period examined when winds of 100 m s^{-1} were observed for a few days duration at 0.4 mb in middle latitudes, a subsequent warming occurred. However, there were two warmings (events E & G) when this upper-wind condition did not occur. Warmings E and G initially indicate easterly wind shears in the upper stratosphere in polar regions and easterly winds very early in the warming process. The formation of an easterly shear layer in the middle stratosphere is favorable for trapping wave energy according to Tung and Lindzen (1979a). Kanzawa (1980) found conditions favorable for trapping vertically propagating waves above 50 km in polar latitudes on January 19, 1973 (warming E) based on cross sections of the latitude gradient of potential vorticity computed from zonal averages of geostrophic zonal wind. This is four days after the initial wind state depicted in Figure 6E.

Where the initial heating is largest in middle latitudes at the time of intermediate warming (events A, C, E, F) the initial wind deceleration is confined to middle latitudes and west winds in the upper stratosphere may actually increase somewhat in polar regions. However, by the time of maximum warming the winds appear to have generally weakened throughout the stratosphere above 10 mb. At this time easterly winds generally appear in the polar stratosphere during major and spring warmings. The post-warming stage finds a further deceleration of the winds throughout the stratosphere with the decrease spreading to the lower polar stratosphere, 10-200 mb, following the descending zonal heating pattern.

e. Wave 1 Momentum Flux

One mechanism for decelerating the mean zonal wind during warmings is through divergence of eddy westerly momentum flux. Thus, momentum flux (uv) was computed for zonal waves each day in the region 35-75N 850-0.4 mb. Geostrophic winds were used in the calculation for both zonal and meridional waves. For all warmings during 1970-74, wave 1 momentum flux was much larger than for other waves and dominated the transport pattern. Figure 7 indicates the wave 1 eddy momentum flux pattern at 2 mb for each warming event. At this altitude the deceleration of zonal winds is appreciable and any relation to the pattern of eddy momentum transport should be apparent.

The basic pattern of westward momentum transport during a warming is not unlike that of heat transport with strong poleward transport of westward momentum occurring during the intermediate and maximum warming stages of the heat flux cycle and equatorward (or weak northward) transport occurring during the pre-warming and post-warming stages. Divergence of eddy momentum flux occurs on the equatorward side of the latitude of maximum momentum transport. This region of divergence appears to move poleward as the warming progresses. This behavior helps qualitatively explain the initial zonal wind deceleration in mid-latitudes and subsequent movement toward polar regions described previously.

Flux convergence of eddy momentum occurs poleward of the latitude of maximum flux, tending to increase the zonal mean west winds near the pole. In the early stages of warming, west winds are often noted to increase in polar latitudes, but as the warming progresses these winds also decelerate (Figure 6). Therefore, to satisfy the momentum budget in polar regions other mechanisms are required.

f. Zonal Mean Meridional Circulation

The deceleration of the zonal west wind is given by the zonal mean momentum budget equation according to

$$\frac{\partial [u]}{\partial t} = f[v] - [\omega]\frac{\partial [u]}{\partial p} - \frac{1}{a\cos^2\theta}\frac{\partial}{\partial \theta}\left(\sum_{k=1}^{6}(uv)_k\cos^2\theta\right) \qquad (1)$$

where ω is vertical motion measured with respect to pressure, p, a is the earth's radius, θ is latitude, brackets indicate a zonal mean, and the momentum flux convergence is evaluated for all waves, k=1-6. A comparable equation describes the sensible heat budget:

$$\frac{\partial [T]}{\partial t} + [\omega][T]\frac{\partial}{\partial p}\left(\ln [\theta_T]\right) = -\frac{1}{a\cos\theta}\frac{\partial}{\partial \theta}\left(\sum_{k=1}^{6}(vT)_k\cos\theta\right) \qquad (2)$$

where T is temperature, θ_T is potential temperature and the heat flux convergence is evaluated for all waves, k=1-6. In these equations, the flux convergence due to wave structure of the vertical motions has been neglected. Further, the temperature change due to radiational cooling in the stratosphere has not been included. Both assumptions appear reasonable (O'Neill,1980), especially when our purpose is only to evaluate the relative strength of the meridional cell, described by $[\omega]$ and [v] as a function of the characteristic steps of the heat flux cycle. For 10-degree latitude belts, the heat flux convergence, 24-hour zonal temperature change and lapse of potential temperature were used in (2) to calculate $[\omega]$ each day at selected levels in the stratosphere. Similarly, the momentum flux convergence, 24-hour zonal wind change, vertical shear of zonal wind and $[\omega]$ from (2) were used to estimate the meridional wind component, [v] in (1).

The computed zonal mean vertical motion $[\omega]$ pattern was strongest at 30 mb while the meridional wind [v] pattern was generally largest at 2 mb or 1 mb. Table 4 indicates the zonal vertical motion $[\omega]$, for each warming event during pre-warming and maximum warming steps of the heat flux cycle. At the time of maximum warming there is strong ascending motion poleward of 70N with somewhat weaker descending motion in middle latitudes. In contrast, weak random vertical motion characterizes the pre-warming state. The meridional velocity [v] at 2 mb, Table 5, indicates a component, generally from the north, of 1-2 m s^{-1} poleward of 70N at the time of maximum warming. During the pre-warming state, the meridional component is less than 1 m s^{-1} and nearly random.

Thus, the meridional indirect thermal cell described in Section 1 (Matsuno, 1971) is characteristic of all the warming processes described here. Northward transport of heat by large-scale eddies produces ascending motion over the pole in the stratosphere and descending motion in middle latitudes. The branch of the cell in the upper stratosphere is a zonal mean north wind which helps decelerate the zonal west wind by the action of the Coriolis torque, -f[v].

PRE-WARMING

Event	77	70	60	50	40	30N
			Latitude			
A	-.3	1.3	.2	- .2	.1	.0
B	.4	.4	.1	.1	-.1	-.1
C	-.7	-.3	.4	.2	-.1	-.1
D	.5	.2	.2	.3	.0	-.2
E	.6	-.1	-.1	-.3	-.2	-.2
F	1.0	.5	-.2	-.4	.0	.0
G	-.3	.4	.2	-.2	-.2	-.2

MAXIMUM WARMING

Event	77	70	60	50	40	30N
A	2.8	.6	-.9	-1.1	-.5	-.1
B	1.5	1.2	-1.1	-.6	.0	.1
C	1.8	1.7	-.2	-1.2	-.6	.1
D	2.4	.3	-.9	-1.1	-.6	-.2
E	2.8	2.3	.0	-1.4	-.9	.0
F	3.2	1.3	-.8	-1.1	-.5	-.1
G	3.5	1.1	-.8	- .7	-.1	.0

Table 4. Zonally averaged vertical velocity (mb day^{-1}) at 30 mb for pre-warming and maximum warming steps of heat flux cycle. Upward vertical motion is positive.

PRE-WARMING

Event	70	Latitude 60	50	40N
A	-.5	-.1	.1	.0
B	.4	.2	.0	.0
C	.2	-.5	-.7	.2
D	-.2	.1	.5	.4
E	-.1	.4	.1	.1
F	-.5	-.7	-.5	.1
G	-.2	.3	.3	.2

MAXIMUM WARMING

A	-3.2	-2.1	-1.8	-.2
B	-1.1	- .9	- .9	-.3
C	-2.4	-1.9	1.9	.3
D	-1.2	.1	.4	-.1
E	-1.1	-1.2	-1.5	-.5
F	- .7	-1.6	-1.5	-.1
G	-1.1	- .8	- .3	-.2

Table 5. Zonally averaged meridional velocity (m s^{-1}) at 2 mb for pre-warming and maximum warming steps of heat flux cycle. Winds from the south are positive.

4. Discussion

The time behavior of wave parameters at all altitudes at 65N is indicated schematically for each warming in Figure 8. On this diagram, time-altitude behavior of the occurrence of easterly winds and the maxima of wave 1 heat flux, zonal temperature, vertical motion and meridional wind are depicted to show how these variables are related. Above 10 mb there is a correspondence between the heat and momentum flux maxima so the latter is not shown. A parameter is also not shown when there is no distinct maximum. Time zero corresponds to the time of maximum 2-mb heat flux for each warming event.

Most apparent is the upward slope of the heat flux maximum from 100 to 10 mb, with increasing time. Closely associated with the heat flux maximum in the upper stratosphere are maximum upward motion and north wind. An exception is warming B where descending motion at high altitudes is indicated, but strong ascending motion does occur at higher latitudes.

Heat flux maxima are observed to precede zonal temperature maxima and the occurrence of stratospheric easterlies by a few days. The zonal mean temperature maximum and subsequent cooling appear first above 10 mb and then move downward. The descending zonal cooling may be the result of the appearance of a critical level as described by Matsuno (1971). Several of the criteria for a critical level as given by Matsuno are apparent, i.e. decreasing heat flux at high levels (warmings A, B, C, Figure 1), occurrence of descending easterly winds (warmings A, B, E, G , Figure 8.), heating (cooling) over the poles and cooling (heating) near the equator below (above) the critical-level (warmings A, B, E, F, G, Figure 5).

There is some evidence to suggest that a weak direct meridional cell may exist just prior to or early in the warming process. The strongest evidence for the cell is the occurrence of equatorward heat and momentum fluxes throughout the stratosphere at the initial pre-warming step (Figures 1 and 7) and the intermittent occurrence of meridional winds from the south early in the warming process as indicated in Figure 8 for events A, C and E. The non-inclusion of radiative cooling in the zonal heat balance equation (2) may have prevented the detection of descending motion near the pole which would further support the existence of a direct cell. A direct cell, if it exists, would transport heat from the pole towards the equator, acting as a refrigerator to further cool polar regions and increase the equator-to-pole thermal gradient. Such a cell is known to increase the zonal available potential energy at the expense of eddy available potential energy and should lead to a strengthening of the polar night jet in middle latitudes. These extreme winds are favorable for trapping vertically propagating planetary waves. Such waves begin to amplify as soon as the meridional thermal cell reverses direction with the switch to poleward heat flux at the start of the warming process.

5. Summary and Conclusions

In this analysis, the evolution of seven Northern Hemisphere warming events is described in terms of wave parameters, from 850 to 0.4 mb, for four winters, 1970-1974. The concept of an indirect thermal cell as described by Matsuno (1971) appears to characterize the warming process for each event. This cell has ascending motion over the pole and descending motion in middle latitudes. The cell is driven by poleward heat transport

by wave 1 throughout the atmospheric column with the return branch being equatorward flow in the upper stratosphere. Wave 1 heat transport is the parameter which behaved most consistently with a well-defined sequence.

The pre-warming initial state is characterized by weak equatorward heat transport throughout the atmospheric column and occurs some two to five weeks before maximum poleward heat flux in the stratosphere. Other characteristics of this initial state include cold polar temperature, and a strong mid-latitude polar night jet at 0.4 mb which would appear capable of trapping upward propagating planetary waves.

Within a few days, organized wave 1 poleward heat transport is evident throughout the atmospheric column with the maximum heat transport occurring first in the troposphere and later in the stratosphere. An intermediate warming step is defined to be the time of maximum poleward 200-mb heat transport. At this time, the phase of wave 1 geopotential height slopes westward with altitude from 850 to 1 mb, favoring vertical propagation of wave energy to high altitudes. From 5 to 1 mb, in middle latitudes, the zonal temperature generally begins to increase and westerly winds begin to decelerate.

The maximum warming step occurs about one week later when poleward wave 1 heat flux at 2 mb is maximum. At this time the meridional thermal cell is most strongly developed with maximum ascending motion and northly wind in the stratosphere near the pole. The most intense zonal heating has now shifted over the pole and westerly winds decelerate throughout the stratosphere. In the troposphere, poleward heat transport has weakened and in some cases is reversed.

The post-warming step is characterized by a return to equatorward heat transport at 2 mb. At this time zonal mean cooling usually is observed between 2 and 0.4 mb in polar regions while heating continues down into the

lower stratosphere and upper troposphere. The descent of the warm layer and accompanying stratospheric easterlies during the major warming events have the characteristics of a critical level as described by Matsuno (1971) and others.

The ascent of the wave 1 heat flux maximum from the troposphere up to 2 mb is a precursor to the stratospheric warming which occurs about one week after the time of the initial ascent. This is no doubt related to the early planetary wave amplification in the lower stratosphere that has been described by Labitzke (1977). Other earlier precursors include the occurrence of equatorward heat fluxes in the stratosphere and persistent strong winds in middle latitudes at 0.4 mb, as much as one month earlier during the pre-warming stage. Shortly afterwards, poleward heat transport begins to occur regularly throughout most of the atmospheric column leading to the eventual warming of polar regions.

For the seven events studied here, differences in the magnitude of zonal heating and west wind deceleration that distinguish major and minor warmings appear to be proportional to the magnitude of the wave 1 heat transport and also to the time interval between the initial prewarming state and the occurrence of maximum heat transport at 2 mb.

Similarities in the behavior of wave parameters during these seven warming events suggest that it may be possible to forecast certain aspects of sudden warmings in advance. The prime variables would be heat transport by the major planetary waves and zonal west winds, both of which could be monitored on a daily basis from the surface upwards to the highest levels in the stratosphere during the winter months. The initial pre-warming state described above would appear to be detectable from these parameters.

Integrating the poleward heat flux from this time to the time of maximum 200-mb heat flux should give an indication of the strength of zonal heating in the stratosphere two to seven days later.

Finally, the events analyzed here indicate that wave 1 was considerably stronger than wave 2. Some other warming events have been predominately wave 2 (Schoeberl, 1978) and the current analysis may not apply. Also, at the time of maximum 2-mb warming, the heat flux at 0.4 mb can be strong and directed equatorward as in event A. Thus, the still unknown dynamics above 0.4 mb probably also contribute substantially to the warming process.

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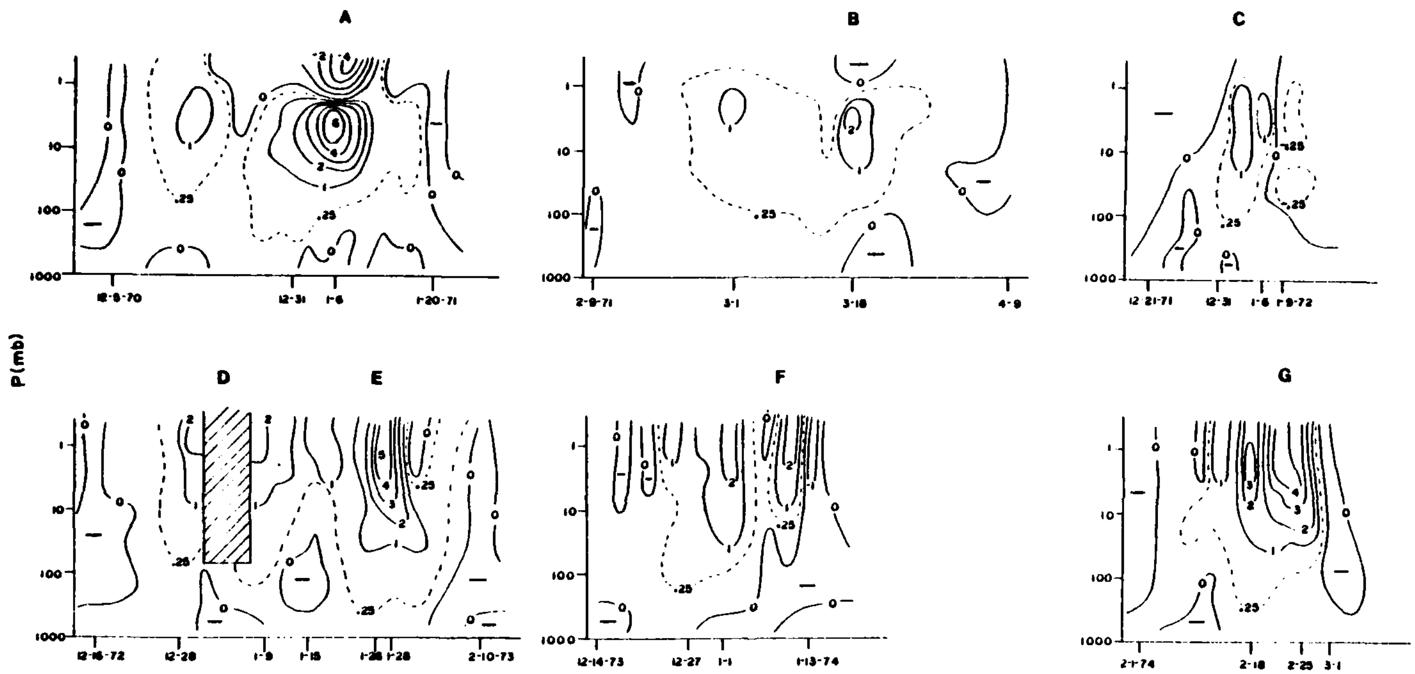
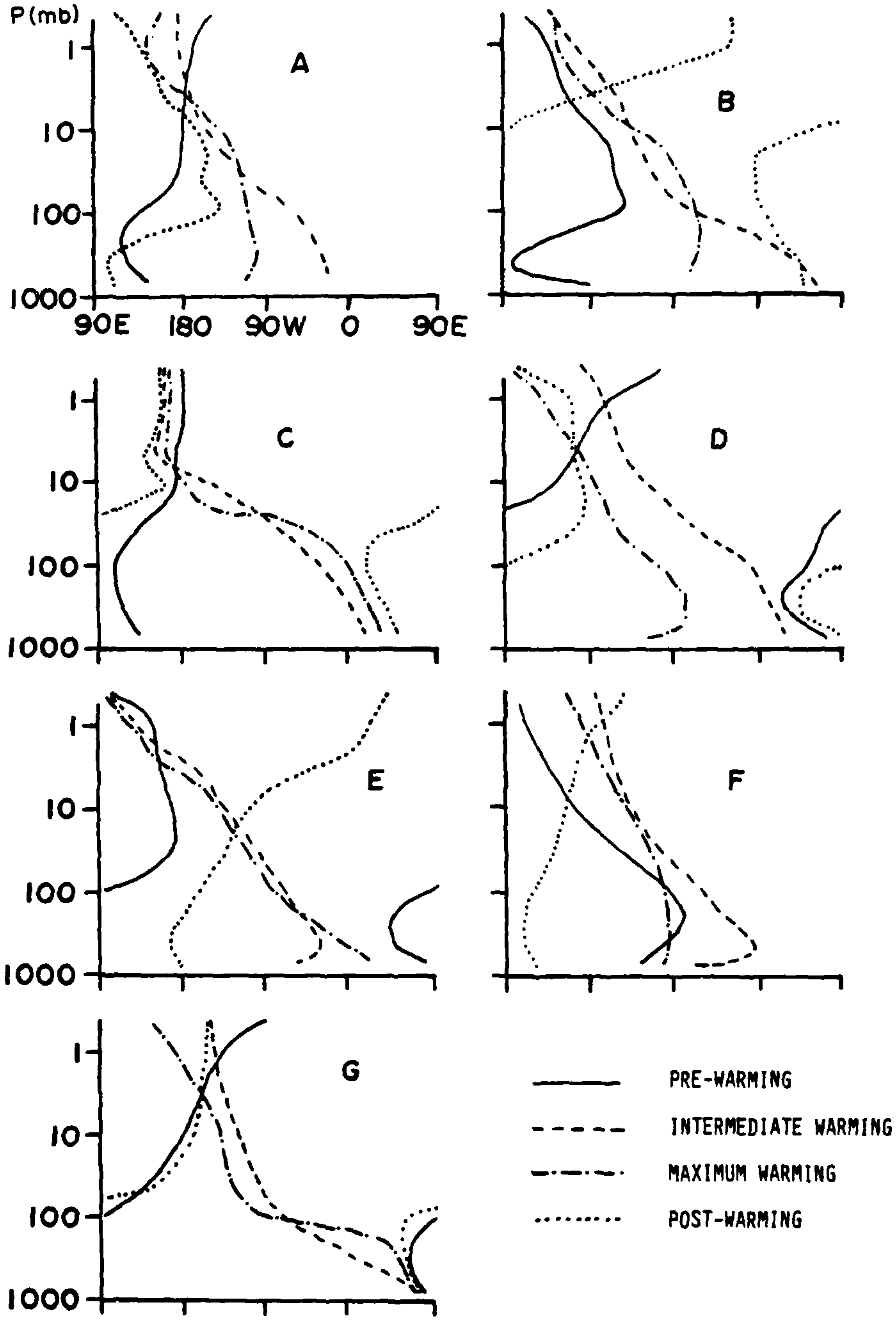
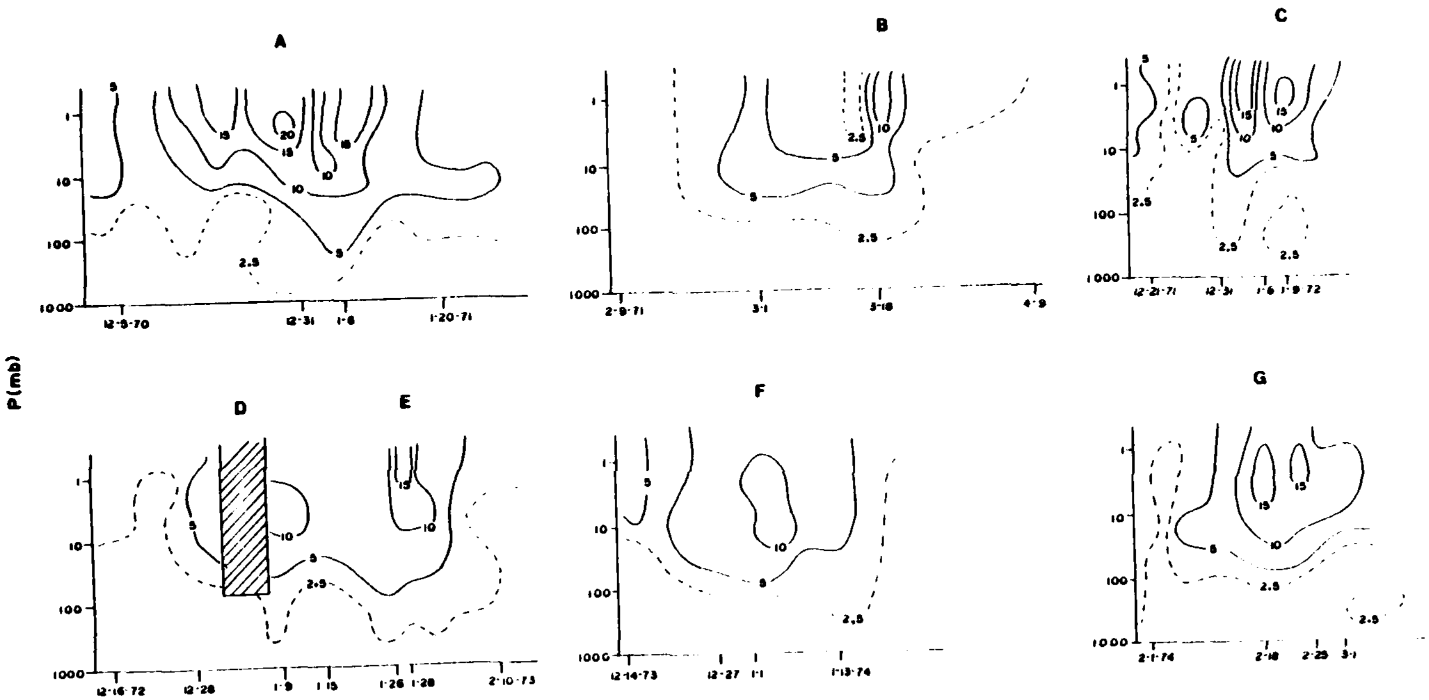


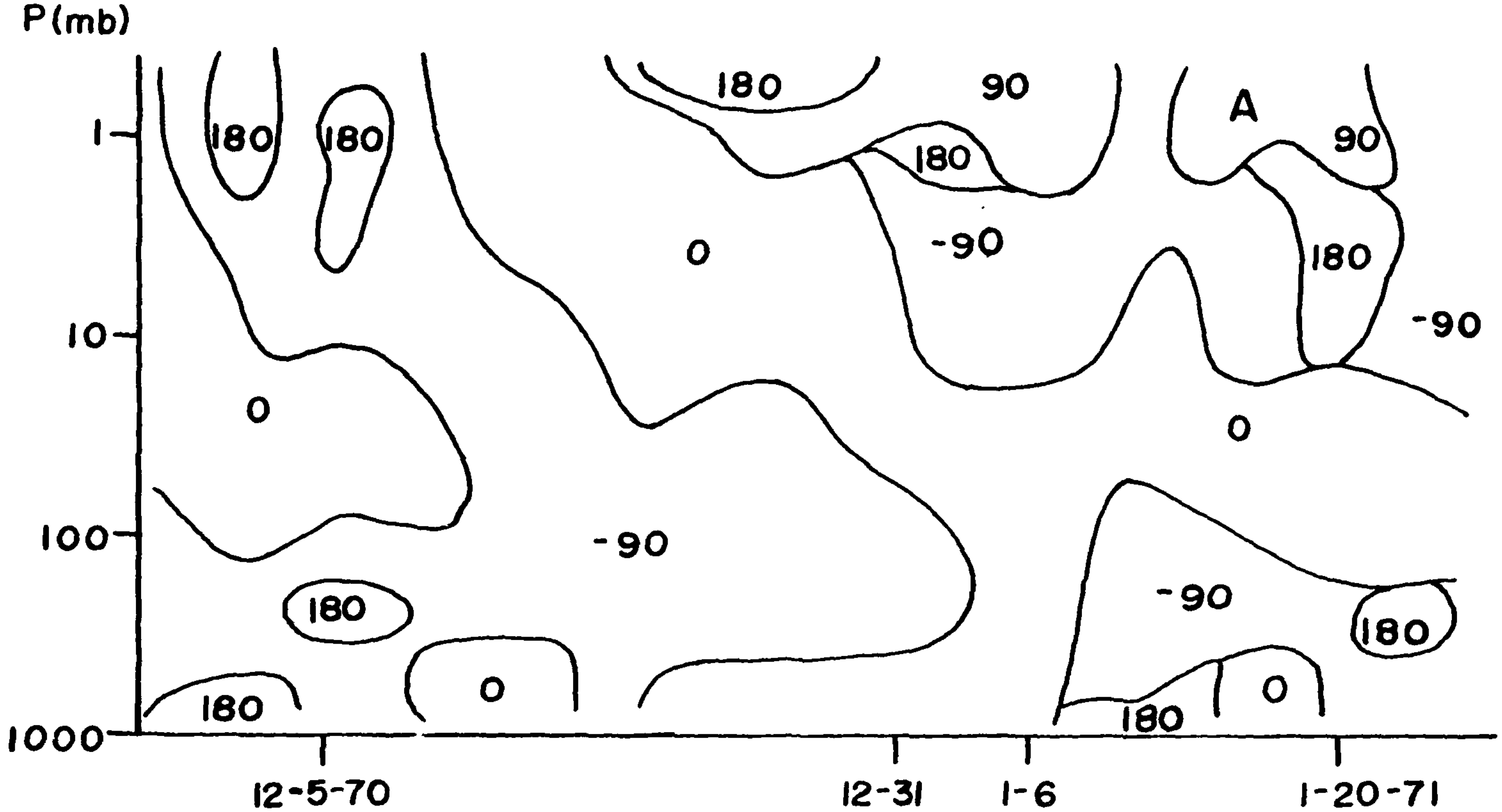
1. Northward transport of sensible heat (10^2 K m s^{-1}) by wave 1 at 65N for seven warming events (A-G).



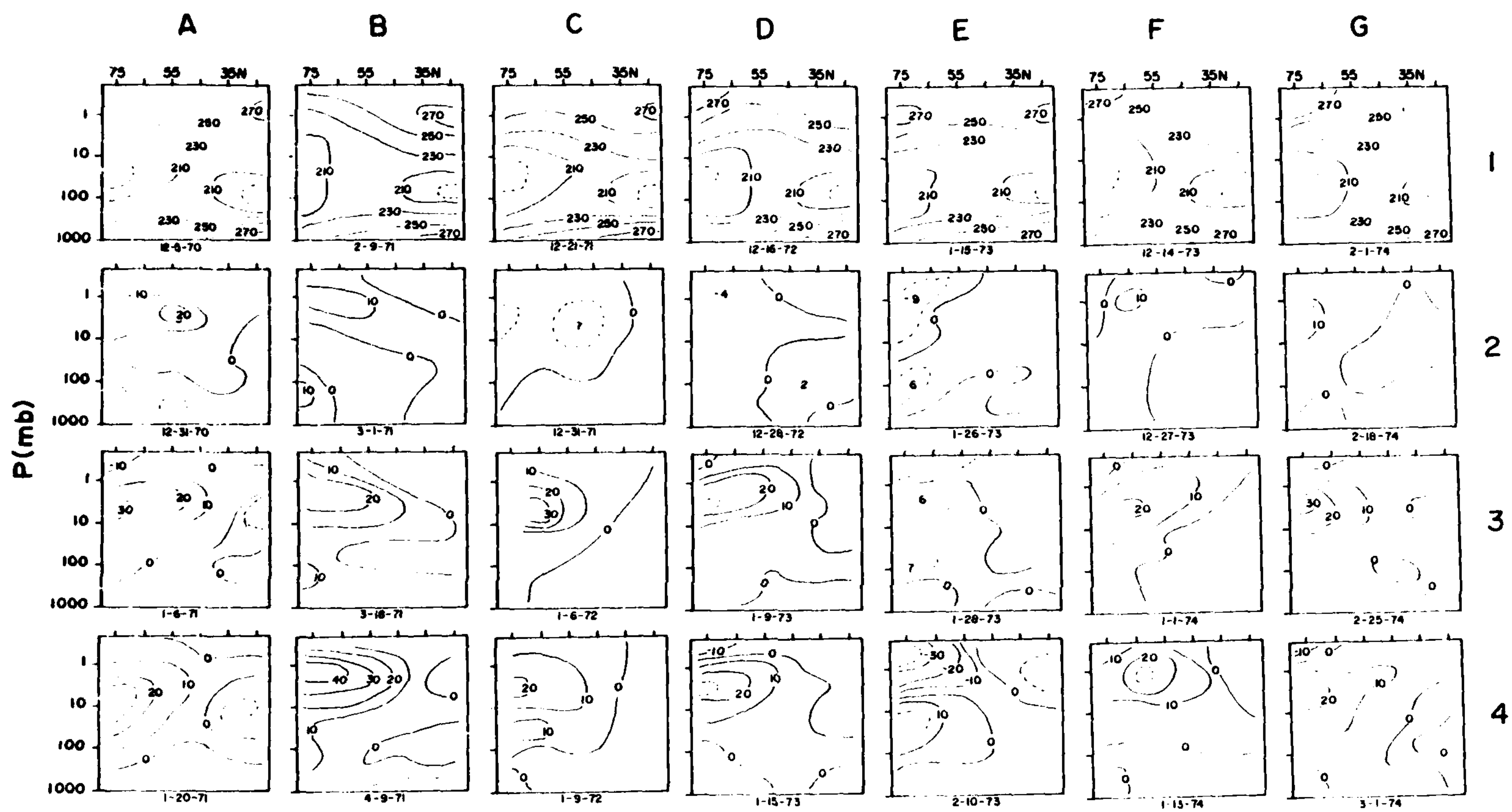
2. Wave 1 phase of geopotential height (longitude of wave maximum), 65N, at four steps in the heat flux cycle.



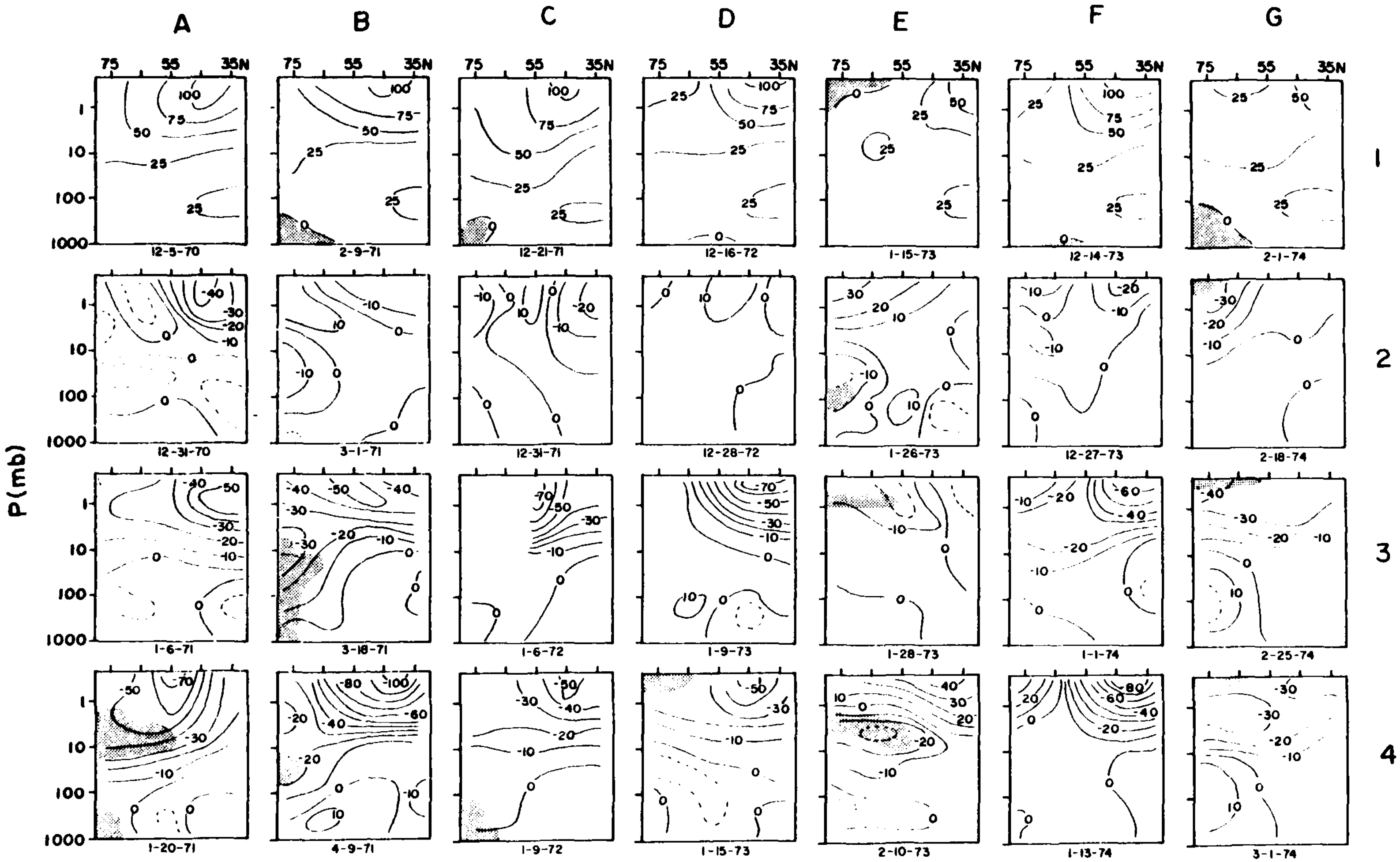
3. Wave 1 amplitude of geopotential height (10^2m) at 65N.



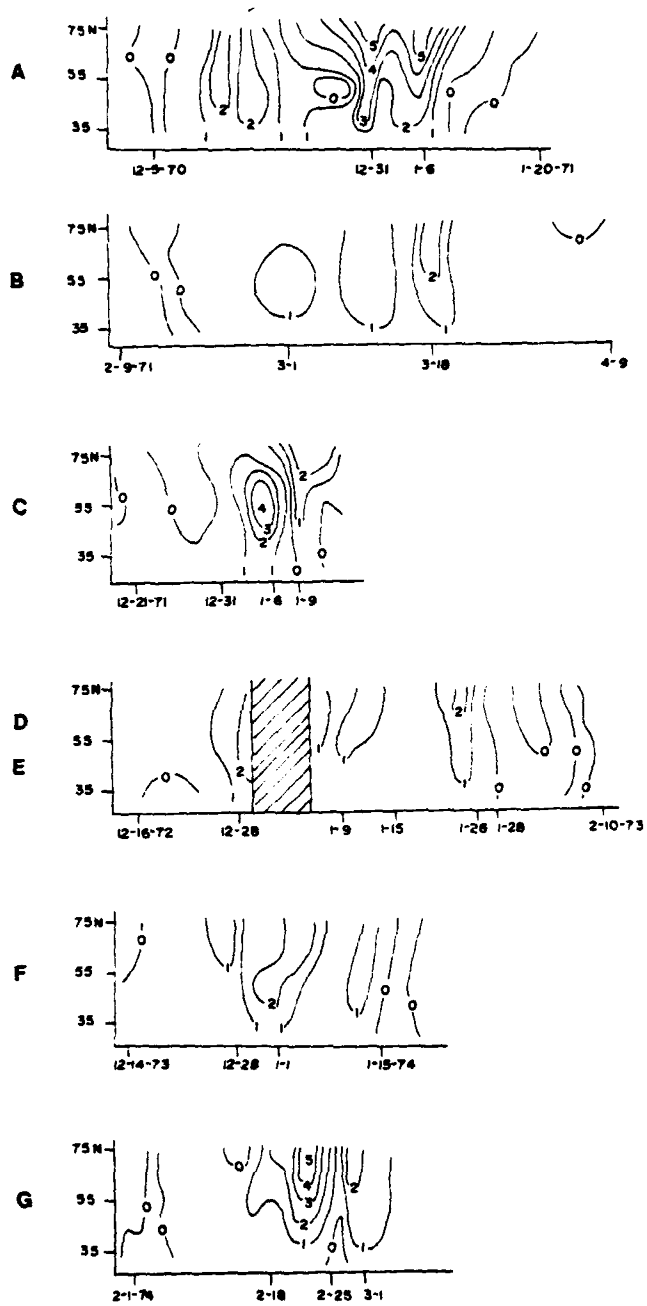
4. Difference between wave 1 phase angles in height and temperature, 65N, for warming event A. A negative difference indicates the temperature wave maximum occurs to the west of the height wave maximum.



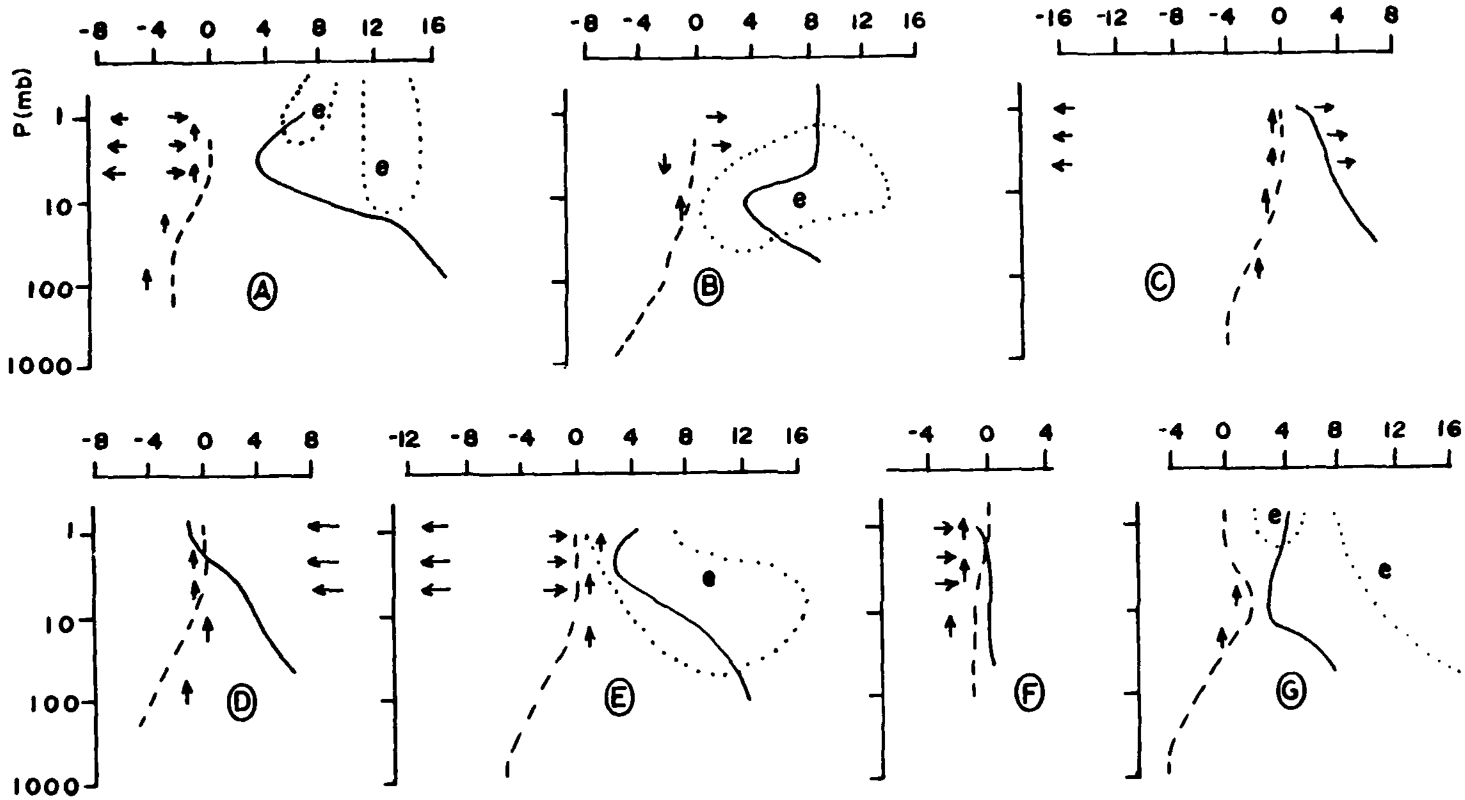
5. Zonal temperature (K) at four steps in the heat flux cycle: Temperature changes from the initial pre-warming state (1), are indicated for intermediate (2), maximum (3), and post-warming (4) steps.



6. Zonal west wind (m s^{-1}) at four steps in the heat flux cycle. Wind changes from the initial pre-warming state (1), are indicated for intermediate (2), maximum (3), and post-warming (4) steps. Stippling indicates zonal easterlies.



7. Northward transport of zonal momentum by wave 1 (10^2 m^2 s^{-2}) at 2 mb.



8. Composite diagram, in days, relative to the date of maximum heat flux at 2 mb, of the behavior at 65N of maxima in all other parameters: wave 1 heat flux (dashed line), zonal temperature (solid line), vertical motion (arrows indicate upward or downward) and meridional wind (arrows pointing to the right are for north wind). Easterly wind regions are enclosed by dotted lines.

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